



Modeling the effect of Russian wheat aphid, *Diuraphis noxia* (Mordvilko) and weeds in winter wheat as guide to management

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Abstract

Infocrop, a generic crop growth model was used to simulate the effect of Russian wheat aphid, *Diuraphis noxia* (Mordvilko) damage on winter wheat at Fort Collins and Akron, Colorado state, USA. Observed and simulated yield reductions in four experiments over a period of two years were found to be closely related ($R^2 = 0.85$). The aphid damage mechanisms coupled to the crop growth model could thus be validated through field experimental data. Economic injury levels for Russian wheat aphids determined with the validated model revealed that winter wheat was more prone to aphid attack during early growth stages than during late tillering and heading. Economic injury level changed among years and were directly related to cost of control but inversely related to market value of winter wheat. Infocrop and GPFARM were used to simulate effect of downy brome weed, *Bromus tectorum* L., at Hays, Kansas state, USA and Cheyenne, Wyoming state, USA and jointed goat grass, *Aegilops cylindrica* Host at Archer, Wyoming, USA on winter wheat. Both models simulated the effect of downy brome on winter wheat well. The average observed and simulated yield reductions with Infocrop over a period of three years were closely related ($R^2 = 0.941$). The effect of

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jointed goat grass on winter wheat was simulated appropriately by GPFARM but not by Infocrop for want of required data on relative weed cover. Validated simulation models can be used for various applications such as for establishing economic thresholds and devising iso-loss curves for the pests. Simulation models have a great potential as guides for optimal pesticide use.

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Keywords: Economic injury level; Russian wheat aphid; Simulation models; Weeds; Winter wheat

1. Introduction

The Russian wheat aphid, *Diuraphis noxia* (Mordvilko) is an economically important pest in many wheat producing countries. It poses a serious threat to small grain production throughout the western United States and some Canadian Provinces (Hein et al., 1990). A yield loss as high as 60% has been observed in wheat due to Russian wheat aphid (Archer and Bynum, 1992). The monetary loss due to this pest was estimated to be \$893 million for 1987–1993 (Morrison and Peairs, 1998). Management practices for this pest have depended on chemical control based on economic thresholds (Legg et al., 1993). The economic threshold is the level of pest population above which it is economical to use a pesticide for pest control, and below which it is not. On the other hand, economic injury level is the minimum pest population density, which causes economic damage. Information on economic thresholds can be used thus to obtain an optimal control of Russian wheat aphids, avoid unwarranted pesticide application, saving producers unnecessary expenditure and conserving the environment (Archer and Bynum, 1992). The economic injury levels may differ among geographic locations and plant growth stages (DuToit, 1986; Hein, 1992; Girma et al., 1993; Archer, 1994).

Downy brome, *Bromus tectorum* L., a winter annual grass, is a serious weed in cultivated crops, forages and rangelands throughout western United States (Morrow and Stahlman, 1984). It is very problematic in winter annual crops such as winter wheat due to their similar growth habits (Blackshaw, 1993). Downy brome has been found to inflict heavy yield loss in winter wheat (Rydrych, 1974; Stahlman and Miller, 1990). Another winter annual grass, jointed goatgrass, *Aegilops cylindrica* Host, causes yield losses worth an estimated US \$145 million annually in winter wheat in western United States (Ogg, 1993). Therefore, proper management of these weed species is essential for ensuring good harvest. Economic thresholds have been developed for downy brome in winter wheat (Stahlman and Miller, 1990). The application of economic thresholds for weeds can help to reduce environmental pollution and the likelihood of herbicide resistance development (Jasieniuk et al., 1999). However, economic thresholds, whether for insect pests or weeds, are based on empirical yield–infestation relationships, which often vary temporally and spatially and are likely to be site specific. Therefore, it would be very expensive and time consuming to use field experiments to establish such yield–infestation relationships for

different pest species, crops, and locations. Crop growth simulation models, based on crop physiological and ecological principles and coupled with pest damage mechanisms, can be used to establish location and weather-specific economic thresholds more quickly and economically. These models can account for changes in weather, soil and other management practices encountered at different locations. The simulation models thus may help to increase the value and efficiency of field experiments substantially.

Keeping this in view, the present study was undertaken to simulate the effect of Russian wheat aphid and two winter annual grass weeds on winter wheat yield and to demonstrate that economic injury levels can be determined through simulation models.

2. Materials and methods

2.1. Simulation of Russian wheat aphid damage

2.1.1. Model description

The effect of Russian wheat aphid on winter wheat yield was simulated through Infocrop, a generic crop growth simulation model developed at Indian Agricultural Research Institute, New Delhi (Aggarwal et al., 2004). It is coupled with different pest damage mechanisms. The pest damage mechanisms can be defined as plant physiological processes affected by pests. Different types of damage mechanisms include germination reduction, stand reduction, light stealing, assimilation rate reduction, assimilate sucking and tissue consumption.

Aphids have been classified as assimilate sappers and light stealers because they suck sap from different plant parts and at the same time also excrete honeydew, which reduces availability of photosynthetic active radiation to the plants. The effect of direct feeding of aphids on winter wheat was simulated by reducing growth rates of green leaves, stem reserves and storage organs depending upon assimilate sucking rate of aphids on respective plant organs as follows:

$$\text{RWLVG} = \text{GCROP} * \text{FSH} * \text{FLV} - (\text{DLV} + \text{SUCKLV}) \quad (1)$$

Definitions of various variables and parameters are presented in Table 1. The model itself calculated the values of the variables while parameter values used are also given in this table.

The allocation of assimilates increased the leaf weight while leaf death due to senescence and aphid sucking reduced it.

$$\text{RWIR} = \text{GCROP} * \text{FSH} * \text{FST} * \text{FSTRT} - (\text{LSTR} + \text{SUCKST}) \quad (2)$$

Assimilates sucked by aphids from stems were subtracted from weight of stem reserves and not from stem weight because a part of these reserves are often available for current growth in wheat.

$$\text{RWSO} = \text{GCROP} * \text{FSH} * \text{FSO} - \text{SUCKSO} \quad (3)$$

Table 1
Variables/parameters of the Infocrop model

Variable/parameter name	Definition
<i>A. Variables</i>	
ATRANS	Actual transpiration from crop and weed canopy (mm day^{-1})
DLV	Death rate of leaves due to senescence ($\text{kg ha}^{-1} \text{day}^{-1}$)
DTR	Daily terrestrial radiation ($\text{MJ m}^{-2} \text{day}^{-1}$)
EFFLAI	Effective leaf area of the crop ($\text{m}^2 \text{leaf m}^{-2} \text{soil}$)
EXP	Exponent function
FLV	Fraction of FSH allocated to leaves
FSH	Fraction of assimilates (GCROP) allocated to shoot
FSO	Fraction of FSH allocated to storage organs
FST	Fraction of FSH allocated to stem
FSTRT	Mobilisable fraction of stem weight
GCROP	Net assimilates available for plant growth ($\text{kg ha}^{-1} \text{day}^{-1}$)
HNYWT	Honeydew production rate of aphids ($\text{kg ha}^{-1} \text{day}^{-1}$)
HONYSM	Total amount of honeydew produced by aphids (kg ha^{-1})
INTGRL	Integral function
KDF	Light extinction coefficient of the crop ($\text{ha soil ha}^{-1} \text{leaf}$)
LSTR	Translocation rate of stem reserves to other parts ($\text{kg ha}^{-1} \text{day}^{-1}$)
NALV	Rate of nitrogen availability to leaves ($\text{kg ha}^{-1} \text{day}^{-1}$)
NAST	Rate of nitrogen availability to stems ($\text{kg ha}^{-1} \text{day}^{-1}$)
NLV	Rate of change of nitrogen in leaves ($\text{kg ha}^{-1} \text{day}^{-1}$)
NLVI	Initial N content of leaves (kg ha^{-1})
NDLV	Rate of nitrogen loss through dead leaves ($\text{kg ha}^{-1} \text{day}^{-1}$)
NDEMISO	Rate of nitrogen demand of storage organs ($\text{kg ha}^{-1} \text{day}^{-1}$)
NDST	Rate of nitrogen loss through dead stems ($\text{kg ha}^{-1} \text{day}^{-1}$)
NTLV	Rate of nitrogen translocation from leaves ($\text{kg ha}^{-1} \text{day}^{-1}$)
NSO	Rate of change of nitrogen in storage organs ($\text{kg ha}^{-1} \text{day}^{-1}$)
NST	Rate of change of nitrogen in stems ($\text{kg ha}^{-1} \text{day}^{-1}$)
NTST	Rate of nitrogen translocation from stems ($\text{kg ha}^{-1} \text{day}^{-1}$)
NUPNH _{1,2,3}	Rate of nitrogen uptake (NH_4) from 1st, 2nd and 3rd soil layer ($\text{kg ha}^{-1} \text{day}^{-1}$)
NUPNO _{1,2,3}	Rate of nitrogen uptake (NO_3) from 1st, 2nd and 3rd soil layer ($\text{kg ha}^{-1} \text{day}^{-1}$)
NUPTK _{1,2,3}	Rate of nitrogen uptake ($\text{NO}_3 + \text{NH}_4$) from 1st, 2nd and 3rd layer ($\text{kg ha}^{-1} \text{day}^{-1}$)
NUPTKT	Rate of nitrogen uptake in three soil layers ($\text{kg ha}^{-1} \text{day}^{-1}$)
NWEED	Total nitrogen uptake by weeds (kg ha^{-1})
NWEEDR	Rate of nitrogen uptake by weeds ($\text{kg ha}^{-1} \text{day}^{-1}$)
PARCRP	Rate of available radiation (pest mediated) to the crop ($\text{MJ m}^{-2} \text{day}^{-1}$)
PARINT	Rate of radiation interception by the crop ($\text{MJ m}^{-2} \text{day}^{-1}$)
PEVAP	Potential soil evapotranspiration (mm day^{-1})
PPOSK	Aphid population on the crop (No. ha^{-1})
PSTPAR	Fraction of effective leaf area affected by honeydew
RWIR	Growth rate of stem reserves ($\text{kg ha}^{-1} \text{day}^{-1}$)
RWLVG	Growth rate of green leaves ($\text{kg ha}^{-1} \text{day}^{-1}$)
RWSO	Growth rate of storage organs ($\text{kg ha}^{-1} \text{day}^{-1}$)
SUCK _{LV, ST, SO}	Assimilate sucking rate of aphids on leaves, stem reserves, and stem organs ($\text{kg ha}^{-1} \text{day}^{-1}$)
SUKN _{LV, ST, SO}	Nitrogen sucking rate of aphids on leaves, stem reserves and storage organs ($\text{kg ha}^{-1} \text{day}^{-1}$)

(continued on next page)

Table 1 (continued)

Variable/parameter name	Definition
TKL _{1,2,3}	Thickness of 1st, 2nd, 3rd soil layer (mm)
TKLT	Total thickness of three soil layers (mm)
TRWEDD	Transpiration rate of weeds (mm day ⁻¹)
TRWL _{1,2,3}	Water uptake rate of roots from 1st, 2nd and 3rd layer (mm day ⁻¹)
WAV _{1,2,3}	Available water in 1st, 2nd and 3rd soil layer (mm day ⁻¹)
WEEDCV	Ratio between weed leaf area and crop leaf area
WLRT _{1,2,3}	Water content in 1st, 2nd and 3rd soil layer (mm)
WLVG	Weight of green leaves (kg ha ⁻¹)
<i>B. Parameters</i>	
FPST _{LV, ST, SO}	Proportion of aphid population (PPOSK) on leaves, storage organs and stems (0.4, 0.2, 0.4)
GFR	Grain filling rate (2 mg day ⁻¹)
GNOCF	Number of grains produced per kg of dry matter (35000 kg ⁻¹)
KDFMAX	Maximum value of extinction coefficient (0.6)
MAXNUP	Maximum rate of nitrogen uptake by the crop (10 kg ha ⁻¹ day ⁻¹)
NHRICE	A factor to prevent NH ₄ uptake by non-rice crops (0.1 for wheat)
RGRPOT	Potential rate of crop growth (0.0099 day ⁻¹)
RUE	Radiation use efficiency of the crop (0.0003 kg MJ ⁻¹ day ⁻¹)
SKINWT	Weight of one aphid (0.4 mg)
SLAVAR	Specific leaf area of variety (0.0024 m ² kg ⁻¹)
SUCKRT	Assimilate sucking rate per unit insect weight (0.45 mg mg ⁻¹ day ⁻¹)
SUKNRT	Nitrogen sucking rate per unit insect weight (0.0089 mg mg ⁻¹ day ⁻¹)
TGBD	Base temperature for reproductive phase of the crop (7.5 °C)
TGMBD	Base temperature for crop germination (3.6 °C)
TTGERM	Thermal time for crop germination (70 °C days)
TTGF	Thermal time from flowering to physiological crop maturity (490 °C days)
TTVG	Thermal time from crop germination to flowering (1010 °C days)
TVBD	Base temperature for vegetative growth (4.5 °C)

The aphid sucking rate on leaves, storage organs and stem reserves were modeled as given below.

$$\text{SUCK}_{\text{LV,ST,SO}} = \text{SUCKRT} * \text{PPOSK} * \text{SKINWT} * \text{FPST}_{\text{LV,ST,SO}} \quad (4)$$

The daily rate of assimilate sucking from different plant parts depended upon sucking rate per unit insect weight per day (SUCKRT), weight of one insect (SKINWT), aphid population per unit area (PPOSK) and fraction of aphid population on different plant parts (FPST_{LV, ST, SO}).

The SUCKRT and SKINWT were used as parameters, their respective default values being 0.45 mg mg⁻¹ insect weight day⁻¹ and 0.4 mg. These values have been derived earlier for *Sitobion avenae* on spring wheat (Rabbinge and Coster, 1984). Fractions of pest population present on leaves, stems and storage organs were also used as parameters with their respective values presumed to be 0.4, 0.2 and 0.4 because leaves and storage organs harbour most of the aphid population while stems contain relatively less population.

Along with carbohydrates, the aphids also remove nitrogen (amino acids) from plants. Effect of aphids on crop nitrogen was simulated by reducing the rate of

available nitrogen in leaves, stems and storage organs depending on nitrogen sucking rate of aphids on respective plant parts.

$$NLV = NLVI + NALV - (NTLV + NDLV + SUKNLV) \quad (5)$$

$$NST = NAST - (NTST + NDST + SUKNST) \quad (6)$$

$$NSO = NDEMISO - SUKNISO \quad (7)$$

The rate of nitrogen availability in various plant organs depends upon rate of potential nitrogen availability and rate of nitrogen loss through various processes including the aphid sucking. The nitrogen sucking rates of aphids on leaves, storage organs and stem reserves were modeled as:

$$SUKN_{LV,ST,SO} = SUKNRT * PPOSK * SKINWT * FPST_{LV,ST,SO} \quad (8)$$

The nitrogen sucking rate per unit insect weight per day (SUKNRT) was used as a parameter with its default value as $0.00892 \text{ mg mg}^{-1} \text{ insect weight day}^{-1}$, which was derived as 2% of SUCKRT. Rossing et al. (1989) observed that amount of nitrogen sapped by pests can be assumed as 2% of the amount of carbohydrates removed by them from the plants. Assimilate sucking by aphids increases the maintenance cost of the crop and thus less assimilates remain available for growth and development.

The light stealing effect of honeydew, excreted by aphids, on plant growth and yield was simulated by reducing effective leaf area of the crop as:

$$PARCRP = 0.5 * DTR * (1 - \exp(-KDF * (EFLAI - PSTPAR))) \quad (9)$$

The honeydew affected fraction of leaf area was subtracted from effective leaf area, which in turn diminished the radiation interception by the crop.

The honeydew affected proportion of leaf area was derived as follows:

$$PSTPAR = EFLAI * (HONYSM / (HONYSM + WLVG)) \quad (10)$$

$$HONYSM = \text{INTGRL}(\text{ZERO}, \text{HNYWT}) \quad (11)$$

$$HNYWT = 0.404 * SUCKRT * PPOSK * SKINWT \quad (12)$$

According to this the effective leaf area was reduced in proportion to ratio between cumulative honeydew weight and total weight of honeydew plus leaves. The cumulative honeydew weight was obtained by integrating the rate of honeydew production by aphids. The honeydew production was assumed to depend upon SUCKRT, SKINWT and pest population per unit area. It has been observed that aphids excrete 40.4% of sucked assimilates as honeydew.

2.1.2. Model calibration and validation

Field experimental data on Russian wheat aphid population densities and winter wheat yield were used for calibration and validation of the model (Randolph et al., 2003). These experiments were conducted during 1992–93 and 1993–94 at Akron (40.10 N, 103.13 W) and Fort Collins (40.35 N, 105.05 W), Colorado State, USA with two winter wheats: ‘TAM 107’, a cultivar susceptible to Russian wheat aphid; and RWA E1, an experimental line resistant to Russian wheat aphid. Fields were split into two 30-m × 60-m strips and each half was planted with either of the

cultivars on 25th September at seeding rate of 68 kg ha^{-1} at Fort Collins and 55 kg ha^{-1} at Akron. The experiment was designed as a randomized complete block with ten treatments (infestation levels) in four replicates for each variety, locality and year. In each variety, a block consisted of a set of four rows chosen at random. Within each of these four rows, ten plots each consisting of a 2-m length of row, were chosen and artificially infested with greenhouse-reared Russian wheat aphid at spring regrowth (early to mid-March) during both years. Ten treatments comprised of nine infestation levels ranging from 100–900 aphids per plot and a control (uninfested crop). The infestation levels were assigned at random to different plots. Each plot was divided into two 1-m row sections, one section for destructive sampling and the other for harvest. Aphid densities were assessed at three growth stages namely tillering, jointing and early heading during the crop season. The crop flowered in mid May and was harvested in July. Only the yield versus infestation data for TAM 107 was utilized in the present study.

The Infocrop-wheat model was calibrated for crop phenology and yield for healthy (uninfested) crop as well as for aphid damage mechanisms. As varietal coefficients were not available for cultivar ‘TAM 107’, default values of these parameters for a general wheat cultivar were used (Aggarwal et al., 2004).

Parameters namely base temperature for germination, base temperature for vegetative growth, base temperature for reproductive phase, thermal time for germination, potential rate of growth, specific leaf area of variety, radiation use efficiency, maximum value of extinction coefficient, number of grains produced kg^{-1} dry matter, potential weight of a grain and grain filling rate were used for model calibration and their values are presented in Table 1.

The Infocrop-wheat was run with weather data of experimental locations and crop management data. The simulated flowering and physiological maturity dates were then matched with observed dates by adjusting thermal time required from crop germination to flowering (TTVG) and from flowering to physiological maturity (TTGF) of the crop. In the process of phenology calibration, their respective values were obtained as 1010 and 490°C .

Two aphid infestation levels were used for calibrating aphid damage mechanisms while the remaining aphid treatments were used for model validation. The parameter SUCKRT was changed from 0.45 (its default value) to 0.3 mg mg^{-1} insect weight while parameter SUKNRT was altered from 0.00892 to 0.006 mg mg^{-1} insect weight during calibration. The calibration for aphid damage mechanisms was done only once, using the 1992–93 Fort Collins results, and the same values of SUCKRT and SUKNRT were retained for simulating other experiments.

2.1.3. Establishment of economic injury levels for the aphid

The validated model was used to develop economic injury levels for Russian wheat aphids to demonstrate the utility of simulation models in pest management. Infocrop was run with different aphid population levels beginning 170 days after sowing (DAS) to 260 DAS, at 10-day intervals, with Fort Collins weather. The economic injury level was calculated by comparing the economic return from the infested crop with that of the healthy crop because economic injury level is the pest

population density at which the infested crop economic return is equal to the economic return of the uninfested crop minus control expenditure.

The economic value of the crop was determined for each population run based on three market prices for wheat namely US \$13, 15 and 17 per 100 kg. Similarly, insecticide expenditures, including costs for insecticide, equipment and labour, were estimated at US \$35 for one spray, \$70 for two sprays and \$105 for three sprays. The effect of weather on economic injury level was examined with Infocrop using Fort Collins weather records for 1993–94, 1994–95 and 1995–96 at wheat price of US \$13 and control cost of US \$35. The effect of different wheat prices on economic injury level was analyzed at control cost of US \$35 with 1993–94 Fort Collins weather, while the influence of control cost on economic injury level was investigated at wheat price of US \$13 with 1993–94 Fort Collins weather.

The economic injury levels were also determined using Akron weather records for 1993–94, 1994–95 and 1995–96 at wheat price of US \$13 and control cost of US \$35.

2.2. Simulation of weed damage

The effect of winter annual grass weed species on yield of winter wheat was simulated with both Infocrop and Great Plains Framework for Agricultural Resource Management Decision Support System (GPFARM) (Ascough et al., 2002; Canner et al., 1998, 2002).

The weeds have been classified as light stealers or more appropriately as resource stealers because they compete for light, nutrients and water with crop plants. Weeds intercept some amount of incident radiation and crop thus receives less radiation than their actual available amount. In Infocrop, the light stealing effect of weeds was accounted for by reducing interception of photosynthetically active radiation in proportion to relative weed cover. The relative weed cover represents the proportion of leaf area of weeds compared to the crop. Many crop growth models require weed biomass as an input for simulating its effect on crop growth and yield. However, we preferred the relative weed cover to the weed biomass because it is easier to estimate it.

$$\text{PARINT} = \text{PARCRP} - \text{PARCRP} * \text{WEEDCV} \quad (13)$$

If total LAI > 3.0, then only competition for light between crop and weeds comes into play because before that sufficient space is available for both crop and weeds to grow independently.

The competition of weeds with wheat for nitrogen was modeled by reducing rate of nitrogen availability to the crop in 1st, 2nd and 3rd soil layer in proportion to relative weed cover as follows:

$$\begin{aligned} \text{NUPNH}_{1,2,3} &= \text{NUPTK}_{1,2,3} * \text{NHRICE} + \text{NUPTK}_{1,2,3} \\ &\quad * \text{NHRICE} * \text{WEEDCV} \end{aligned} \quad (14)$$

$$\begin{aligned} \text{NUPNO}_{1,2,3} &= \text{NUPTK}_{1,2,3} * (1 - \text{NHRICE}) + \text{NUPTK}_{1,2,3} \\ &\quad * (1 - \text{NHRICE}) * \text{WEEDCV} \end{aligned} \quad (15)$$

NHRICE is a factor, which is used to prevent nitrogen uptake in ammonical form in non-rice crops such as wheat. The presence of weeds in field increases nitrogen uptake thereby reducing nitrogen availability for the crop. The rate of total nitrogen uptake has been calculated as

$$\text{NUPTK}_{1,2,3} = \text{MAXNUP} * \text{TKL}_{1,2,3} / \text{TKLT} \quad (16)$$

The rate of nitrogen uptake from three soil layers has been added to get total nitrogen uptake such that

$$\text{NUPTKT} = \text{NUPTK}_1 + \text{NUPTK}_2 + \text{NUPTK}_3 \quad (17)$$

The rate of nitrogen uptake by weeds was calculated as

$$\text{NWEEDR} = \text{NUPTKT} * \text{WEEDCV} \quad (18)$$

Total nitrogen uptake by weeds was obtained by integrating rate of nitrogen uptake such that

$$\text{NWEED} = \text{INTGRL}(\text{ZERO}, \text{NWEEDR}) \quad (19)$$

Similarly the competition of weeds for water was simulated by reducing water availability to crop as a consequence of water loss through weeds from three soil layers. The amount of water content in different soil layers has been modeled as follows:

$$\text{WL}_{1,2,3}\text{RT} = \text{WAV}_{1,2,3} - \text{TRWL}_{1,2,3} * (1 + \text{WEEDCV}) \quad (20)$$

The presence of weeds in the field increases the water loss through transpiration, which is of course always taking place through crop plants. The rate of transpiration from weeds was calculated based on actual transpiration and potential soil evaporation with respect to relative weed cover.

$$\text{TRWEDD} = \text{ATRANS} * \text{WEEDCV} + \text{PEVAP} * \text{WEEDCV} \quad (21)$$

The actual transpiration was determined as

$$\text{ATRANS} = \text{TRWL}_1 + \text{TRWL}_2 + \text{TRWL}_3 \quad (22)$$

GPFARM is whole-farm, strategic planning model that has been linked to a weed interference and simple demography model (WISDEM) (Ascough et al., 2002) to predict the long-term impact of management on weed populations. WISDEM simulates variation in weed population over time, and consequent yield loss due to weeds, in response to crop rotation, tillage system and specific weed management tactics (Canner et al., 1998). The model uses an innovative weed population dynamics structure, which summarizes demographic processes of annual weeds including seed mortality, seedling emergence, herbicide- and tillage-based weed control and density-dependent weed seed production. Calculation of yield loss from weed population density is empirical. Yield loss is predicted with a hyperbolic relationship between crop yield loss and weed density for the most competitive weed in a crop with additional parameters to account for the competitiveness of different weed species and time of emergence of the weeds (Canner et al., 2002). It is well documented that the relationship between crop yield loss and weed density can be described with a rectangular hyperbolic model (Cousens, 1985). Parameters of

the equation are deterministic and do not vary based on any description of weather during a simulation. As GPFARM is a decision support system, it was directly used to simulate yield loss due to weeds under experimental weather and crop management conditions.

2.2.1. Simulation of effect of downy brome

Published experimental data (Stahlman and Miller, 1990) on winter wheat yield reduction and downy brome density (plants m^{-2}) were used for calibration and validation of both models. These experiments were conducted under dry land conditions at Hays (38.53 N, 99.20 W), Kansas State, USA during 1984–85, 1986–87 and 1987–88 with winter wheat cultivar ‘Newton’ and at Cheyenne (41.08 N, 104.49 W), Wyoming State, USA with winter wheat cultivar ‘Buckskin’ during 1986–87. The crop was sown between September 19 and October 30 during different years at Hays and on August 28, 1986 at Cheyenne. The plot size was 1.2×1.2 m. Nitrogen was applied at 35–45 kg ha^{-1} as preplant treatment to wheat. The experiment was conducted in randomized complete block design with a factorial arrangement having four replicates. Different densities of downy brome, planted about 20 days after wheat sowing, constituted various treatments along with a weed free plot. Final density of the downy brome in the plots was estimated in early spring. The winter wheat flowered during mid May and it was harvested in July.

Six weed densities were input into the GPFARM, which predicted weed densities and corresponding yield reductions. Since the maximum weed density generated by GPFARM was 30 plants m^{-2} , Infocrop was used to assess observed yield reductions up to 65 plants m^{-2} . Infocrop required relative weed cover to simulate effect of weeds on crop, which was determined as the ratio of number of weeds to the total weeds plus crop plants per unit area. We assumed a winter wheat stand density of 100 plants m^{-2} at 20 cm inter-row spacing. This approach was adopted to determine relative weed cover as downy brome and winter wheat have similar growth habits and thus similar competitive ability (Blackshaw, 1993). Infocrop was calibrated for crop phenology and uninfested crop yield and weed damage mechanisms. Two weed densities from the 1984 data were used for calibrating weed damage mechanisms, and the remainders were used for model validation. Calibration for weed damage mechanisms did not result in any parameter value changes. Likewise the GPFARM was run with crop management data and different weed pressures and it generated weed densities and yield reductions.

2.2.2. Simulation of effect of jointed goat grass

The effect of jointed goat grass, *A. cylindrica* Host, on winter wheat yields at Archer (41.25 N, 104.75 W), Wyoming State, USA was simulated with GPFARM and Infocrop. Published data on jointed goat grass density versus winter wheat yield loss were used to calibrate and validate the models (Jasieniuk et al., 1999). Spring seedling densities were used to simulate the effect of this weed on winter wheat yield during 1994–95. The procedure for calibration and validation of models was similar to that of downy brome given above.

2.2.3. Simulation of effect of other weed species on winter wheat yields

The purpose of this study was to determine if weed density data could be converted to relative weed units for use in Infocrop, independent of species or if information on weed growth patterns is needed as well. GPFARM and Infocrop were used to simulate the effect of different species of weeds namely kochia (*Kochia scoparia* (L.) Schrad), volunteer rye (*Secale cereale*), wild oats (*Avena fatua* L.) and nightshade (*Solanum ptycanthum* Dun.) on winter wheat at Fort Collins from 1992 to 1998. Models were run with typical dry land production practices. Six weed densities were input into GPFARM, which in turn predicted weed densities at sowing and crop maturity, as well as resulting yield reductions. Predicted weed densities were converted to relative weed cover by dividing number of weed plants by total number of crop and weed plants m^{-2} . For winter wheat the plant stand was taken as 100 plants m^{-2} . Infocrop was run with relative weed cover values calculated by GPFARM and yield losses were estimated. Simulated losses were averaged over a period of seven years and compared to those of GPFARM. Observed yield loss data were not available for comparison.

3. Results and discussion

3.1. Simulation of Russian wheat aphid damage in winter wheat

At Fort Collins during 1992–93, simulated yield reductions ranged from 24.3% to 82.2% in comparison to observed yield reductions of 15.4% to 84.6% (Fig. 1A). Aphid densities ranged from 100 to 1000 aphids per tiller. Simulated and observed yield reductions were similar, indicating that Infocrop simulated Russian wheat aphid induced winter wheat yield losses appropriately (Fig. 2A, Table 2)

On the other hand, simulated yield reductions varied from 82.1% to 97.6% compared with 36.2% to 95.1% observed reductions during 1993–94 at Fort Collins (Fig. 1B). Aphid densities ranged from 500 to 6000 aphids per tiller. Simulated yield reductions exceeded 97% for aphid densities above 1000 aphids per tiller. This differed greatly from observed reductions at aphid densities ranging from 500 to 2000 aphids per tiller. These differences may be due to sampling error. Russian wheat aphid densities exceeding 1000 aphids per tiller are unusual and yields at such levels would be negligible. The combined regression for two years showed close proximity between simulated and observed yield reductions with the exception of a few data points (Fig. 2B, Table 2).

Russian wheat aphid densities were much lower at Akron in both years, ranging from 10 to 100 aphids tiller⁻¹ in 1992–93 and 50 to 250 in 1993–94. Simulated yield reductions ranged from 3.2% to 27.1% compared with 2.6% to 34.9% observed reductions during the first year (Fig. 1C). During the second year, the range of simulated reductions was from 14.5% to 50.2% while observed yield reductions varied from 12.5% to 43.9% (Fig. 1D). Fewer pairs of simulated and observed yield reductions were available for Akron, so a combined two year regression was performed, which indicated that simulated and observed yield reductions were

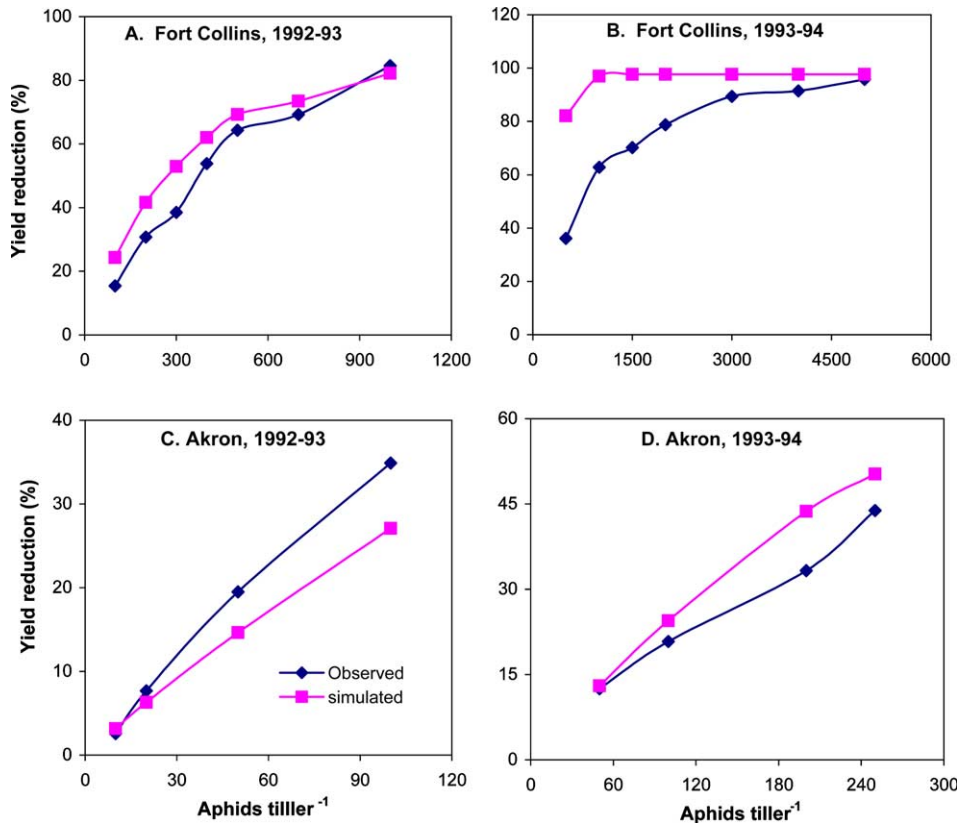


Fig. 1. Observed and simulated yield reduction due to Russian wheat aphid in winter wheat.

similar and that Infocrop simulated Russian wheat aphid induced yield losses satisfactorily (Fig. 2C, Table 2).

Infocrop simulated the Russian wheat aphid damage on winter wheat suitably at both locations in both years, with the exception of a few population levels at Fort Collins in 1993–94 (Fig. 2D, Table 2). The aphid damage mechanisms linked to Infocrop were thus validated with field observations of Russian wheat aphid induced winter wheat yield reductions. The validated model could be used for applications such as determination of site specific economic injury levels for Russian wheat aphid. The aphid damage mechanisms coupled in the Infocrop are: (i) assimilate loss due to direct aphid feeding, and (ii) reduction in light interception due to excretion of honeydew. In the model, the honeydew has been presumed to act by reducing effective leaf area of the crop. Besides causing assimilate loss to crop, Russian wheat aphid injury also resulted in leaf rolling, which reduced leaf area. Unlike other aphid species, honeydew in this case remained inside rolled leaves and did not affect light interception. The Infocrop could still simulate the pest damage because direct feeding of the pest itself accounted for both the damage mechanisms.

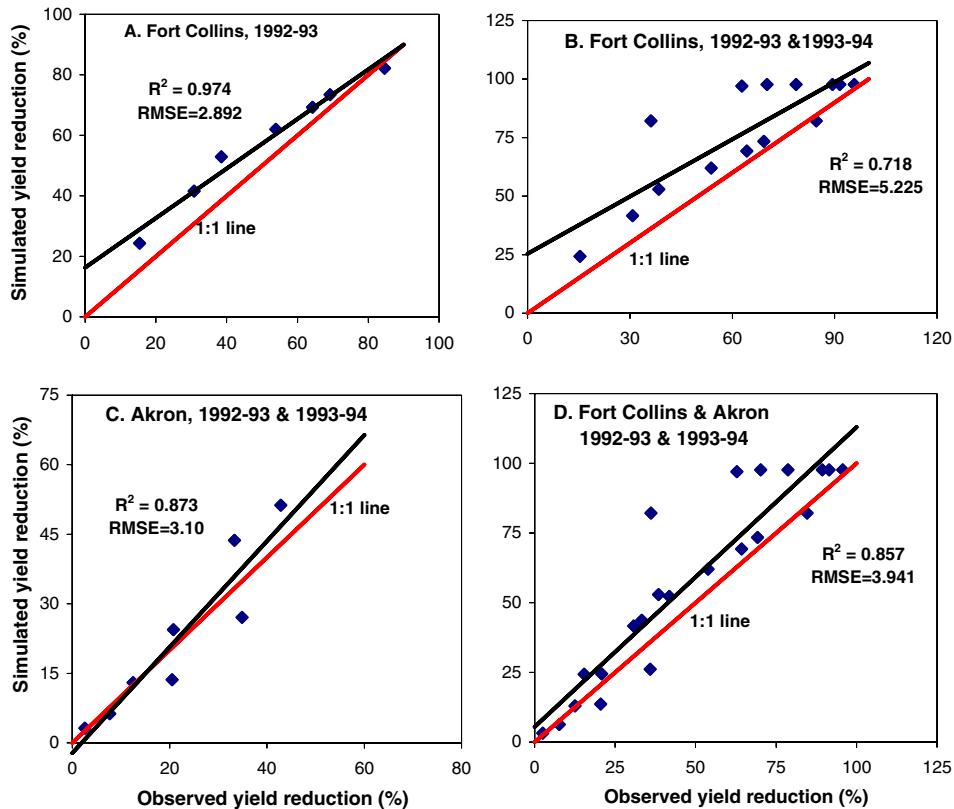


Fig. 2. Regression between observed and simulated yield reduction due to Russian wheat aphid in winter wheat.

Table 2

Goodness of fit between observed and simulated yield reductions due to pests in winter wheat

S. No.	Experimental data used in the study	Pest involved	Coefficient of determination (R^2)	Root mean square error (RMSE)
1	Fort Collins, Colorado, USA (1992–93)	Russian wheat aphid	0.974	2.892
2	Fort Collins (1992–93 and 1993–94)	Russian wheat aphid	0.718	5.225
3	Akron, Colorado, USA (1992–93 and 1993–94)	Russian wheat aphid	0.873	3.10
4	Fort Collins and Akron (1992–93 and 1993–94)	Russian wheat aphid	0.857	3.941
5	Hays, Kansas, USA (1984–85, 1986–87 and 1987–88)	Downy brome	0.582	1.926
6	Hays (3 years average)	Downy brome	0.941	1.055
7	Cheyenne, Wyoming, USA (1986–87)	Downy brome	0.938	1.441

The effect of grain aphid, *Sitobion avenae* (Fabricius) in winter wheat has been simulated through SUCROS by assuming that modeling the effect of aphids on the crop is similar to modeling grain growth as both are sinks for carbohydrates and nitrogen and the supply is partitioned among them (Rossing et al., 1989). It was also found that honeydew produced by aphids reduces the maximum rate of photosynthesis and increases the rate of maintenance respiration of the crop.

3.1.1. Simulation of economic injury levels for Russian wheat aphid

Simulated economic injury levels depicted the wheat crop to be more prone to Russian wheat aphids during early growth stages than later growth stages (Fig. 3A). More aphids damage occurred on young wheat plants than on later growth stages namely late tillering and early heading. The simulated economic injury level for Russian wheat aphid was approximately 10 or fewer aphids per tiller during

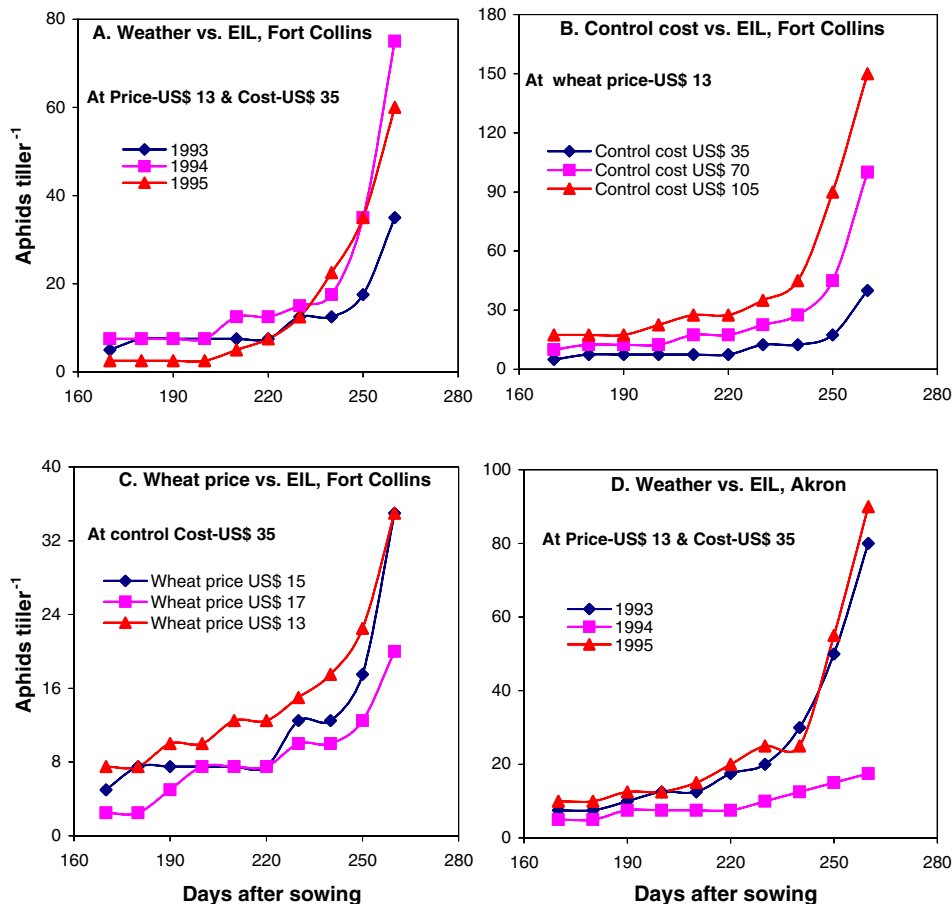


Fig. 3. Economic injury levels (EIL) for Russian wheat aphids on winter wheat.

early spring regrowth stages of the crop (Fig. 3A). At a threshold density of 10 aphids tiller⁻¹, yields of infested plants started to differ from those of uninfested control plants (Kieckhefer and Gellner, 1992). With other parameters constant, the economic injury level varied among years due to changes in weather, which in turn affected yield–infestation relationship (Fig. 3A). There also was a direct relationship between economic injury level and expenditure on control measures (Fig. 3B). The economic injury level was highest at the control expenditure required for 3 sprays, as expected, because as control expenditures increase, more yield loss is required to justify the expense. Similarly, there was an inverse relationship between economic injury level and market price of the commodity (Fig. 3C) because greater crop value requires less proportional loss to justify treatment expense.

The economic injury levels at Fort Collins were higher during 1993 and 1995 but less during 1994 as compared with Akron (Fig. 3A and D). Adoption of same economic injury level at different locations thus does not seem justified, as these are site specific. The simulation models can help us to generate a site-specific economic injury level that is otherwise a difficult proposition through field experiments.

Without an economic threshold, the only option for avoiding yield loss is to treat upon detection of the pest in the crop (Legg and Archer, 1998). Therefore, determination of the economic injury level for an insect species is critical for developing an integrated pest management system. Consequently, economic injury levels must be applicable to wide range of climatic zones, production practices and plant stages. However, economic injury levels developed from empirical relationships are site specific.

It is impractical to conduct the required field experiments for each location. Alternatively, validated crop-pest models can be used to calculate economic injury levels for site-specific conditions (Nordh et al., 1988). Similarly, simplified pest models or simplified decision rules from crop-pest models have been used for managing sweet corn common rust (Teng, 1987), wheat diseases (Zadoks, 1984, 1985), and rice blast (Surin et al., 1991). Detailed simulation models have been used to design strategies for insecticide use (Heong, 1990) and to predict disease epidemics (Teng et al., 1978).

3.2. Simulation of effect of downy brome in winter wheat

The two models were similar in their underestimation of the effect of downy brome on winter wheat yield at Hays during 1984–85 (Fig. 4A). Infocrop simulations were more appropriate at lower downy brome densities than at higher densities. Comparison between observed and simulated yield reductions averaged over three years showed that both models slightly underestimated yield reductions at lower downy brome densities and overestimated at higher weed densities (Fig. 4B). In general, these simulated yield reductions better at lower downy brome densities than at higher densities. GPFARM generated a maximum weed density of only 30 plants m⁻², which in turn limited the level of yield reductions (Fig. 4B).

The regression between observed and Infocrop simulated yield reductions during three years showed moderate relationship between the two (Fig. 5A, Table 2). On the other hand the regression between observed and simulated yield reductions averaged

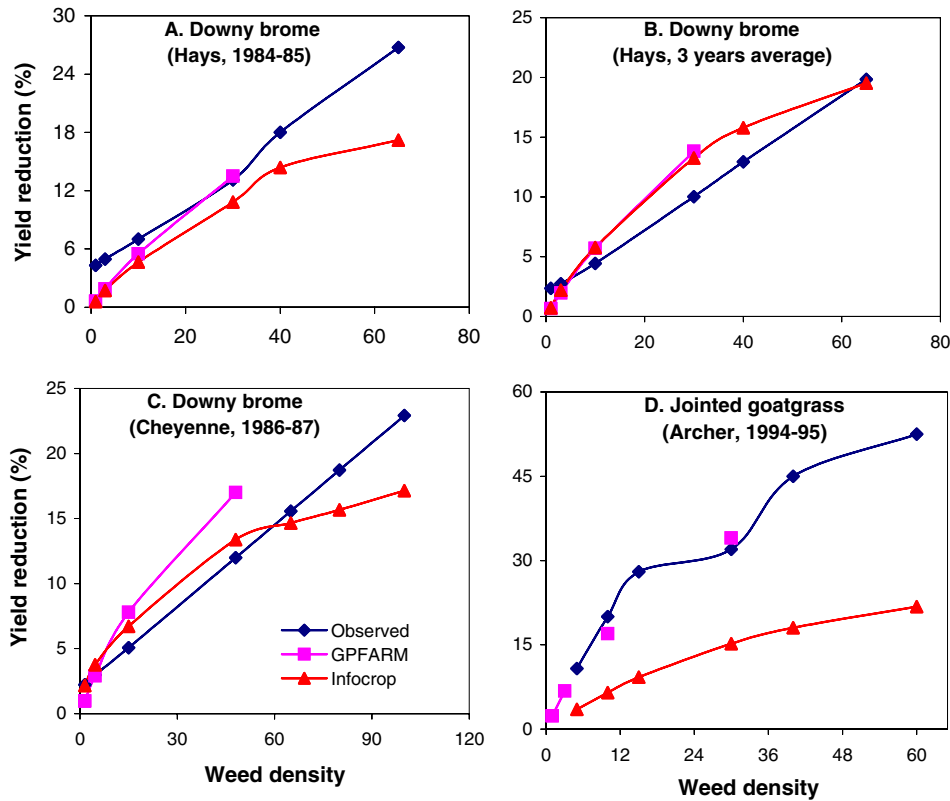


Fig. 4. Observed and simulated yield reduction due to weeds in winter wheat.

over three years, showed very close relationship between the two (Fig. 5B, Table 2). The regression between observed and simulated yield reductions with GPFARM was not worked out due to lesser pairs of values.

At Cheyenne during 1986–87, GPFARM, within limited weed densities, slightly under predicted the yield loss at lower densities and over predicted it at higher weed densities. On the other hand Infocrop estimated yield loss close to observed yield loss at all weed densities except at highest weed density of 100 plants m^{-2} (Fig. 4C). The regression between observed and Infocrop simulated yield reductions showed very strong relationship between the two (Fig. 5C, Table 2). Overall the models simulated the effect of downy brome on winter wheat well. GPFARM and Infocrop results were similar because the growth habits and competitive abilities of downy brome and winter wheat are similar, thus allowing the conversion of weed density to relative weed cover.

As with Russian wheat aphid, a validated model for simulating downy brome effects on winter wheat yields could be used for economic thresholds for downy brome infestations in a variety of situations. Economic thresholds for downy brome have been approximated from empirical relations (Stahlman and Miller, 1990),

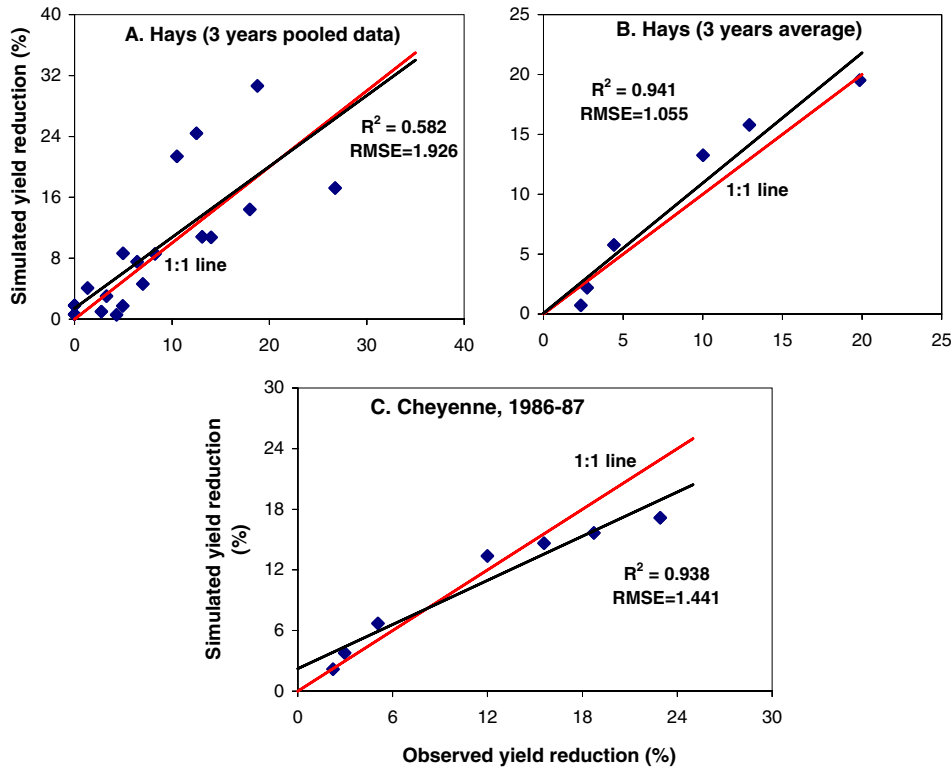


Fig. 5. Regression between simulated and observed yield reduction due to downy brome in winter wheat.

however studies have shown that crop yield and yield loss – weed density relations can vary considerably between sites and years (Jasieniuk et al., 1999). This instability in crop–weed interference relationships suggests that economic threshold densities should be calculated for each key weed species, major crop variety, crop field and weather conditions, which is impractical and unrealistic. However, validated simulation models can be used to account for the influences of these variables on the weed–crop yield relationship, thus allowing the use of site specific economic thresholds.

3.3. Simulation of effect of jointed goat grass on winter wheat

GPFARM suitably simulated the effect of jointed goat grass on winter wheat at Archer within the limited range of weed densities available in this model (Fig. 4D). In contrast, Infocrop greatly underestimated the effect of jointed goat grass on winter wheat yields due, in part, to the lack of data on relative weed cover, a required Infocrop input. As a result, relative weed cover had to be estimated by proportional weed density compared to total crop and weed density. This comparison assumes equal competitiveness for the crop and jointed goat grass, while in reality jointed goat grass is more competitive than winter wheat. The conversion of jointed goat grass density

data to relative weed cover would require information on growth habit and leaf area index in addition to plant counts.

3.4. Simulation of effect of other weed species on winter wheat

Although Infocrop slightly overestimated the effect of kochia, *K. scoparia* on winter wheat yield at Fort Collins, the simulated yield reductions for these weed species were similar for the two models (Fig. 6A). Infocrop underestimated the effect of volunteer rye, *S. cereale*, on winter wheat yields (Fig. 6B) because this weed species is more competitive than winter wheat. GPFARM was unable to simulate yield reductions due to wild oats, *A. fatua* and the nightshade species, *S. ptycanthum* as weed densities as high as 30 plants m⁻² did not cause any decline in yield (Fig. 6C and D). Relative weed cover, calculated from weed densities, can be used in Infocrop to simulate winter wheat yield reductions due to kochia infestation. However, additional information on growth habit and leaf area index would be required in order to use relative weed cover to simulate yield reductions due to volunteer rye infestation. Further, GPFARM needs to be modified to allow accurate simulations of the effects of wild oats and nightshade species on winter wheat yields.

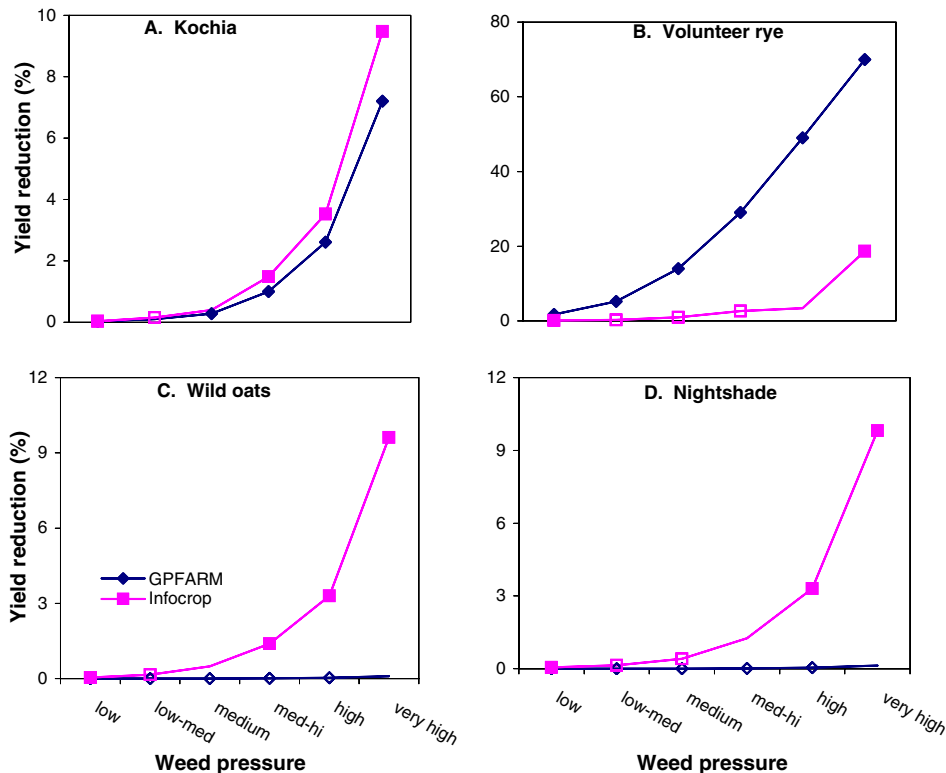


Fig. 6. Simulated yield reduction in winter wheat due to weeds at Fort Collins.

4. Conclusions

Infocrop simulated effect of Russian wheat aphid on winter wheat appropriately and both models simulated the effect of downy brome on winter wheat yield satisfactorily. Such validated models have potential pest management applications, including the calculation of site-specific economic thresholds for these pest species under diverse situations. The establishment of such economic thresholds through field experiments would be impractical. The simulation model thus can enhance efficiency of field experiments greatly. The adoption of economic thresholds will promote need-based pesticide application, which will curtail expenditure on unwarranted pesticide application and also reduce environmental contamination.

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